NATIONAL ENERGY TECHNOLOGY LABORATORY

Overview of NETL's High Temperature Heat Transfer and Film Cooling Test Facility

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National Energy Technology Laboratory

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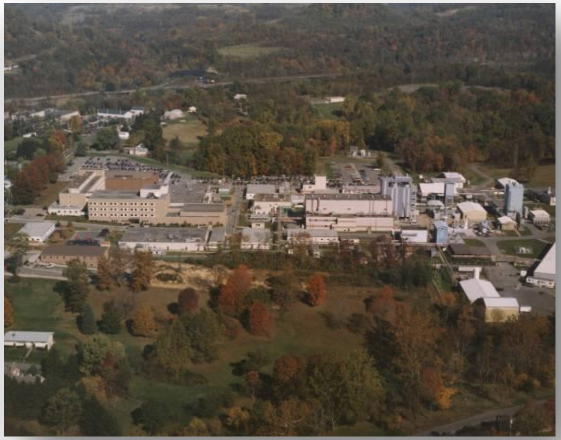
Columbus, OH

National Energy Technology Laboratory

MISSION
Advancing energy options to fuel our economy, strengthen our security, and improve our environment

Oregon

Pennsylvania



West Virginia

NETL Full-Spectrum Capacity for Innovation

1	*DOE national laboratory dedicated to energy RD&D*	• *Economy-wide perspective on energy challenges* • *100 years of energy technology RD&D experience*
2	*Only government owned & operated DOE national laboratory*	• *Unbiased approach reflecting national priorities* • *Direct taxpayer accountability for funding*
3	*Combination of research expertise and contracting capabilities*	• *Expertise & equipment to perform & evaluate RD&D* • *Collaboration, contracting, counsel, communication*
4	*Established relationships within academia, industry & governments*	• *Broad vision of the energy technology landscape* • *Roundhouse for intellectual capital & tech transfer*
5	*Market-facing basic & applied science*	• *Explicit targets to deliver technology innovations* • *Public / private cost sharing*

National Energy Technology Laboratory

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  - Strategic Energy Analysis & Planning
  - Public Affairs
  - Chief Counsel
    - Legal
    - Environmental Compliance
  - Strategic Center for Natural Gas & Oil
    - Natural Gas & Oil Project Management
  - Strategic Center for Coal
    - Coal & Power R&D
      - Sequestration
      - Existing Plants
      - Power Systems
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    - Energy Delivery Technologies
  - Research & Development
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    - Energy System Dynamics
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    - Geosciences
    - Chemistry & Surface Science
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    - Materials Performance
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    - Earth & Mineral Science
  - Institutional Operations
    - Administrative Support
    - Information Technology
      - Infrastructure Ops & Engineering
      - Information Solutions & Engineering
    - Environment, Safety, Security & Health
      - Environmental
      - Safety & Health
      - Security / ERO
    - Human Resources
      - Employee Relations
      - Staffing & Classification
    - Site Operations
      - Engineering
      - Facility Management
  - Business Operations / CFO
    - Inst. Assurance, Risk Management & Audit Oversight
    - Finance
      - Budget Development, Analysis & Forecasting
      - Gen. Acct., Cost Mgmt & Financial Reporting
    - Acquisition & Assistance
      - Assistance Operations A
      - Assistance Operations B
      - Acquisition & Analysis

Effective 06/19/2011

Regional University Alliance

NETL's Institute for Advanced Energy Studies

Carnegie Mellon University

West Virginia University

Virginia Polytechnic Institute

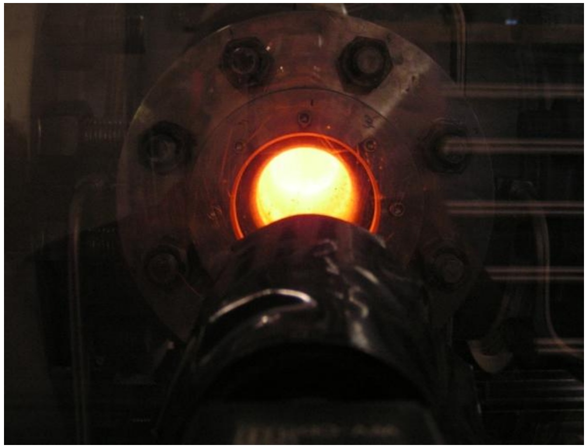
Pennsylvania State University

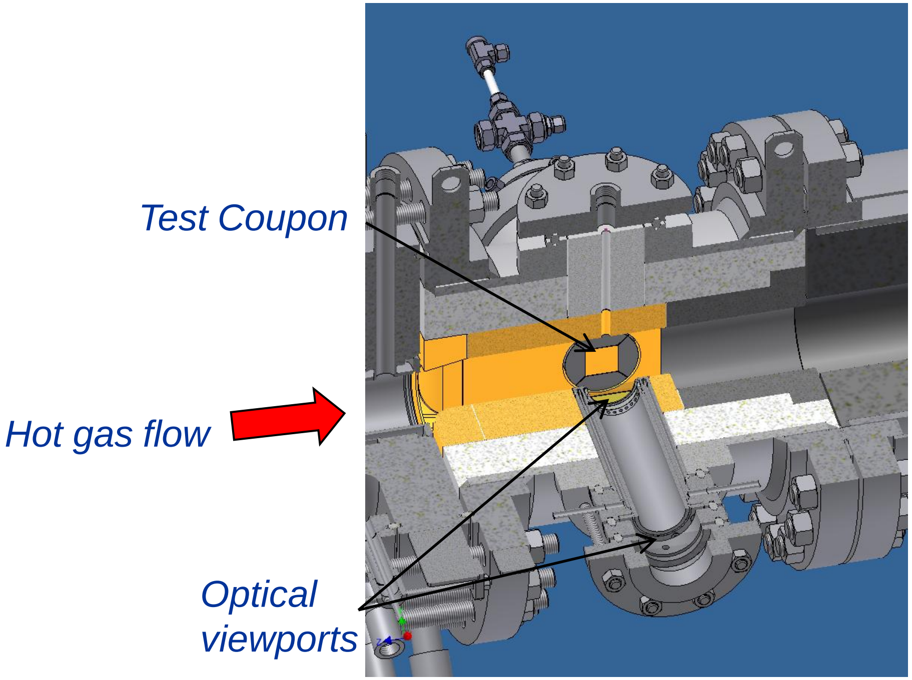
University of Pittsburgh

Leveraging National Lab and University-Based Scientific and Engineering Assets to Address Significant National Energy Issues

Outline

- **Overview high temperature/high pressure test facility**
  - Hardware and facility capabilities
  - Experimental approach
  - Optical surface temperature mapping
  - Lessons learned
- **Overview results of collaboration with University of Pittsburgh**
- **Future work**
- **Summary**





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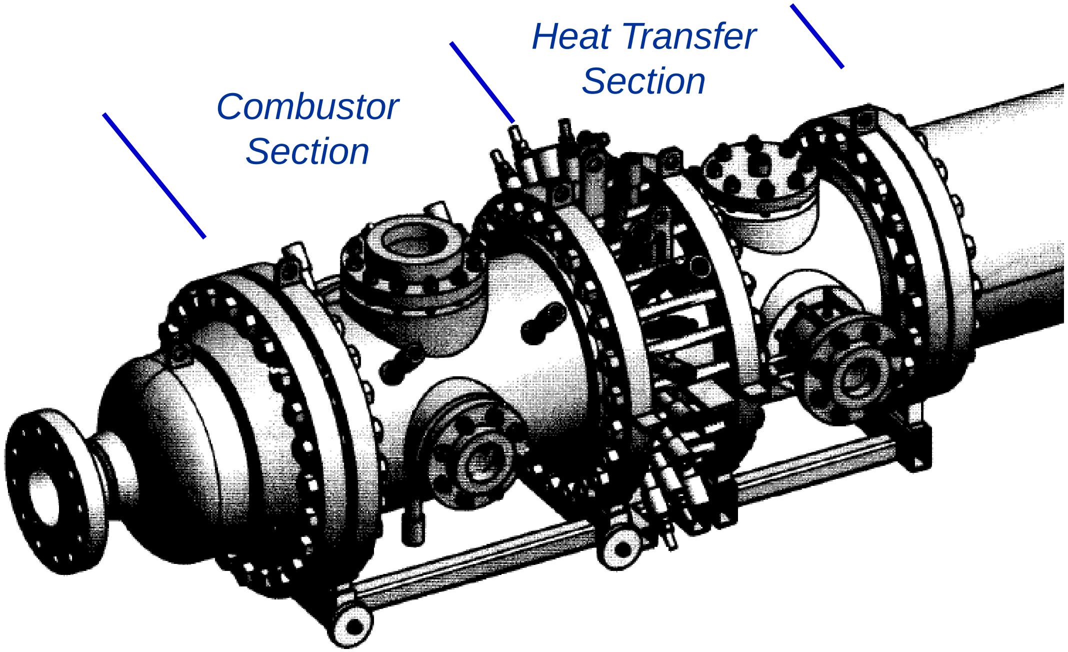
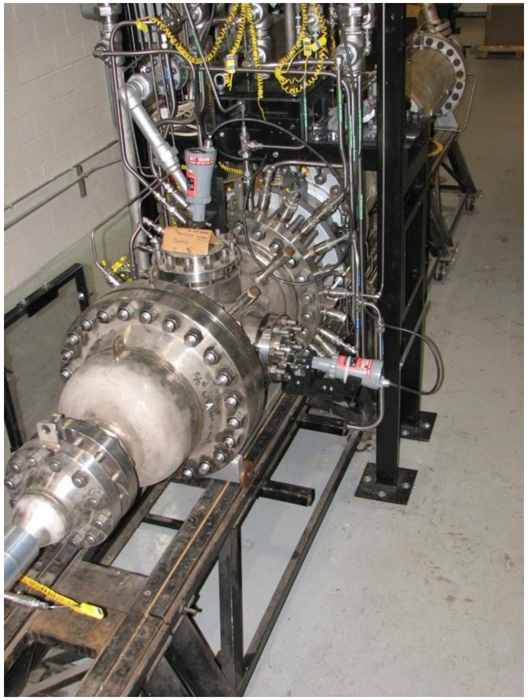
Project Background

- **Modify an existing high pressure combustion rig**

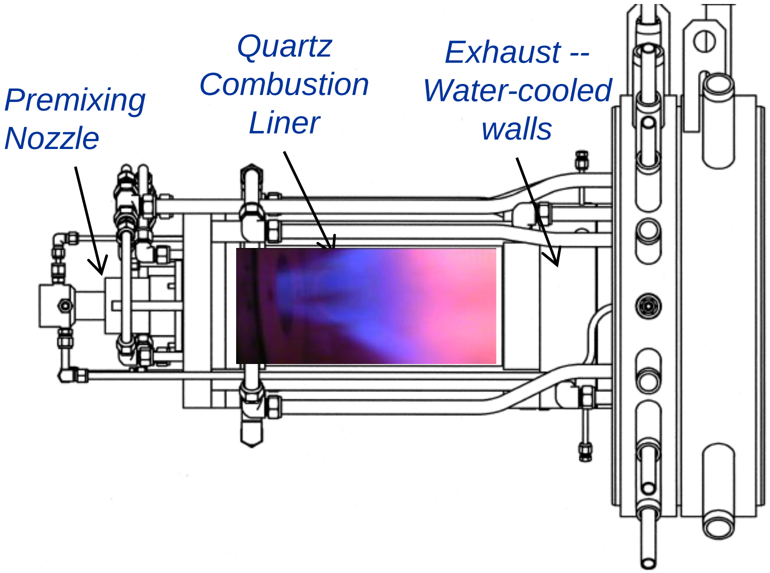




- **Provide "realistic" hot gas path conditions for collaborative efforts**
- **"Proof-of-concept" testing for cooling and sensors**
  - Intermediate scale facility

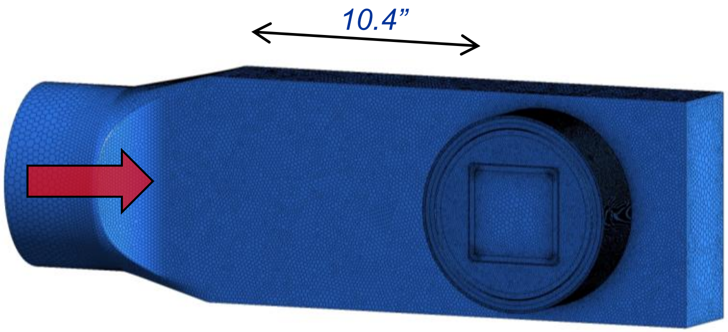
Facility and Rig Capabilities

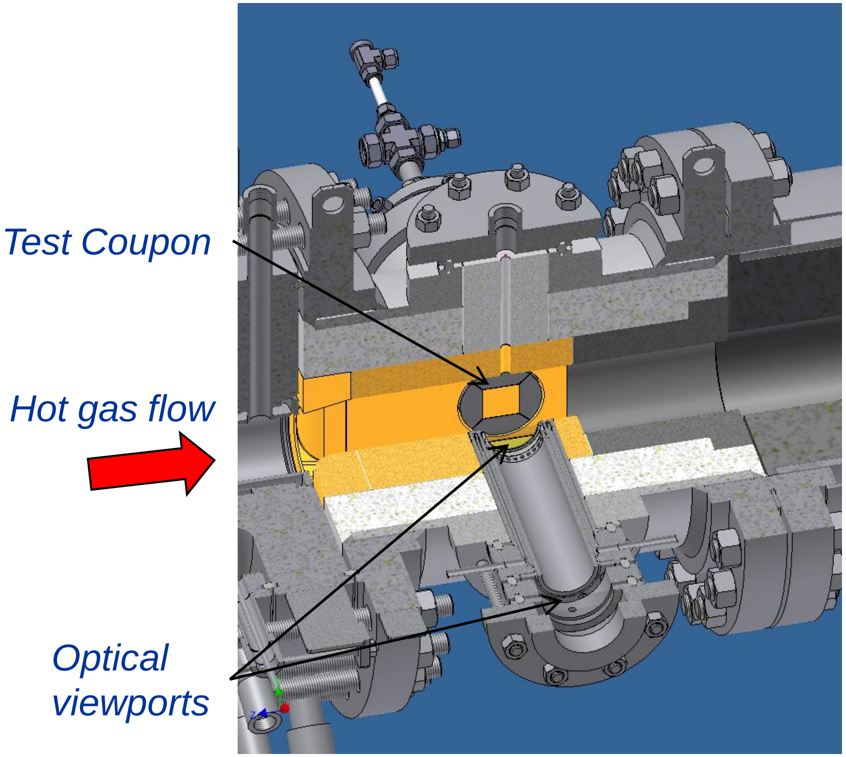
- **Facility capabilities**
  - 2 lb/s air flow @ 700 psi
  - 800-900 F air preheat (independent control)
- **Rig capabilities**
  - 2 lb/s air flow @ 10 atm
  - Max inlet air temperature (800F)
  - Natural gas or hydrogen fuels
- **Combustor design**
  - Swirl-stabilized
  - Lean premixed gaseous fuel
  - Diffusion pilot (12 jets)
  - Quartz combustor liner
    - No dilution cooling jets
    - No upstream film cooling



Experimental Setup

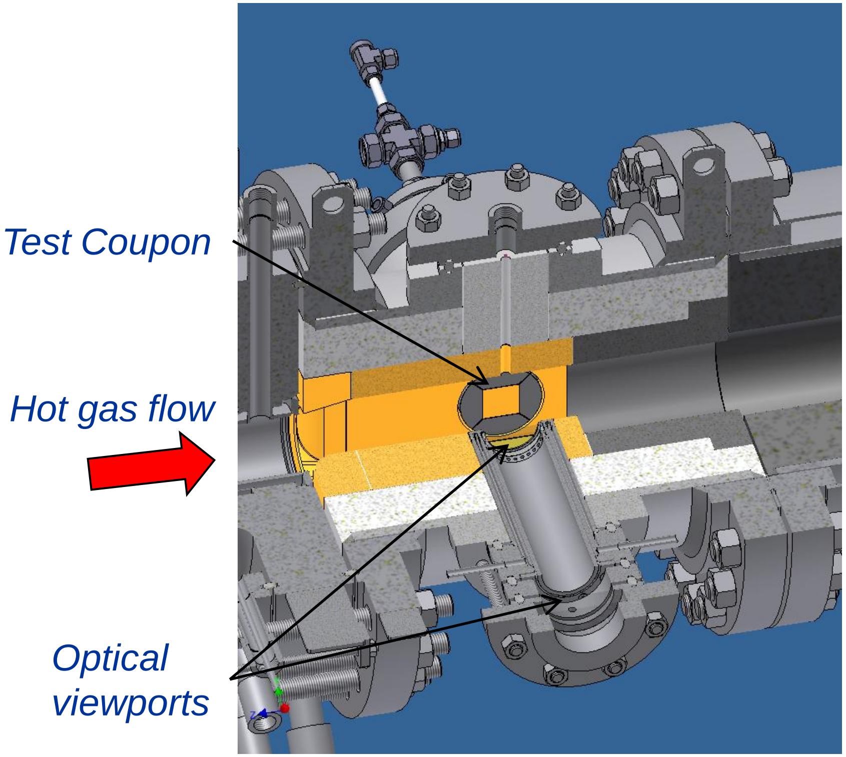
- **Heat transfer section**
  - Refractory lined walls
  - Transition to rectangular cross-section
    - Nominal 4” ID to 5”x 2” flow channel
  - Test samples
    - Haynes 230 coupons
      - 2” x 2” x 0.25” thick
    - Flush with interior walls
    - With and without TBC’s
  - External viewport
    - Commercial quartz flange
  - Internal viewport
    - 3” OD x ½” thick quartz
    - Flush with inner wall



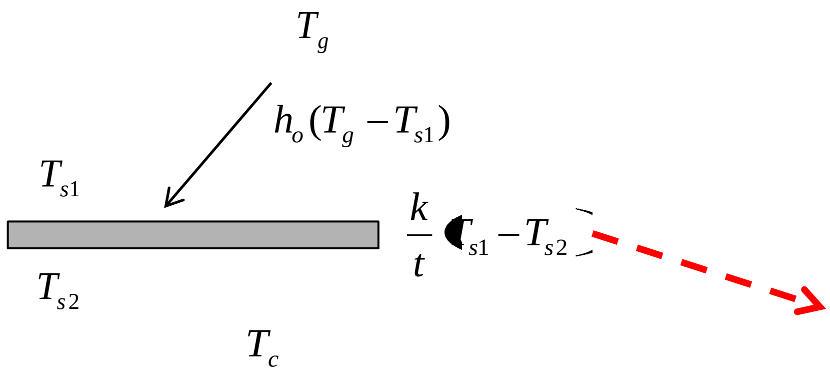


Independent Parameters

- **Operating pressure (1-10 atm)**
- **Hot gas temperature (1000C → ?)**
- **Hot gas path velocity**
  - Limited by flashback and blowoff in combustor premixer
- **Cooling air mass flowrate**
  - Blowing ratio
- **Test sample design**
  - Without TBC
  - With TBC
  - Film cooling design



Experimental Approach



- **Measure q'' with and without coolant flows**

$$\Delta q_{red} = 1 - \frac{q''_{coolant}}{q''_{uncooled}}$$

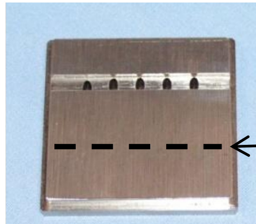
- **Calculate heat flux**
  – q''=k ΔT/Δt

- **Gas temperature is measured using TC**

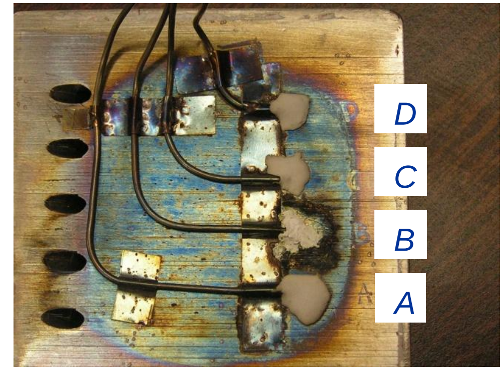
- **Calculate heat transfer coefficient, h_o**
  – $h_o = q''/(T_g - T_{s1})$

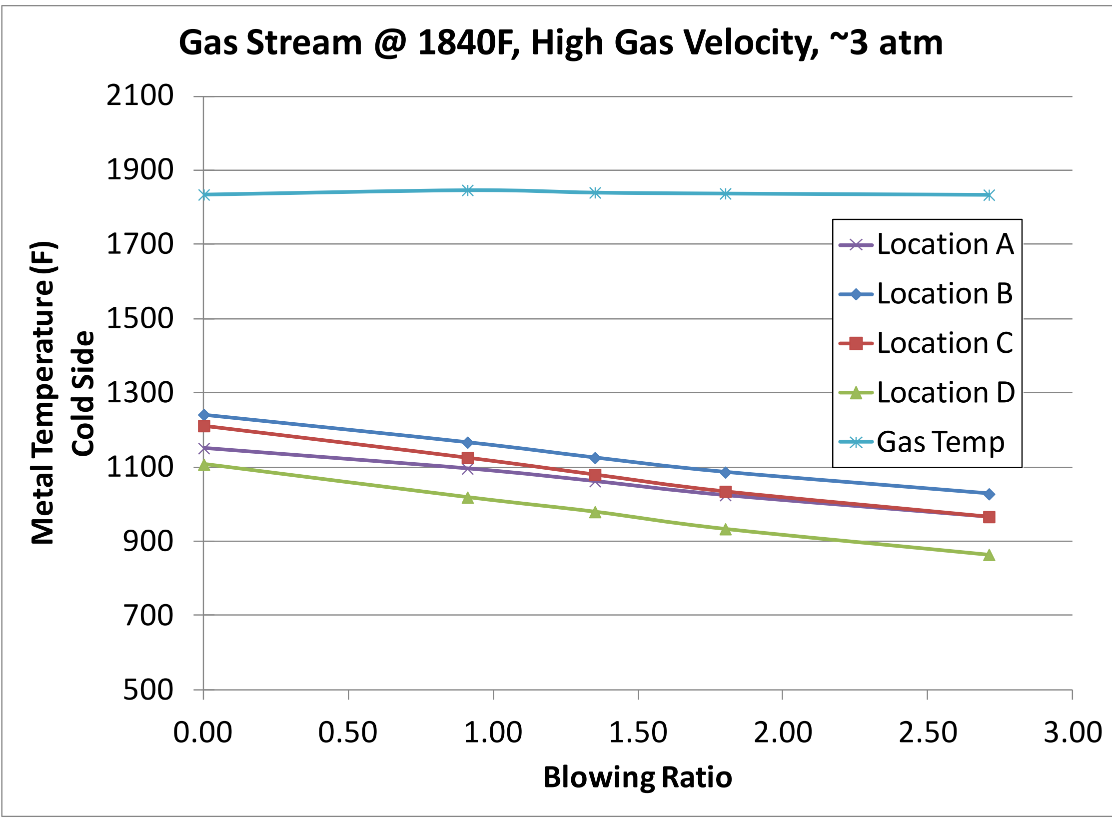
How are surface temperatures measured?

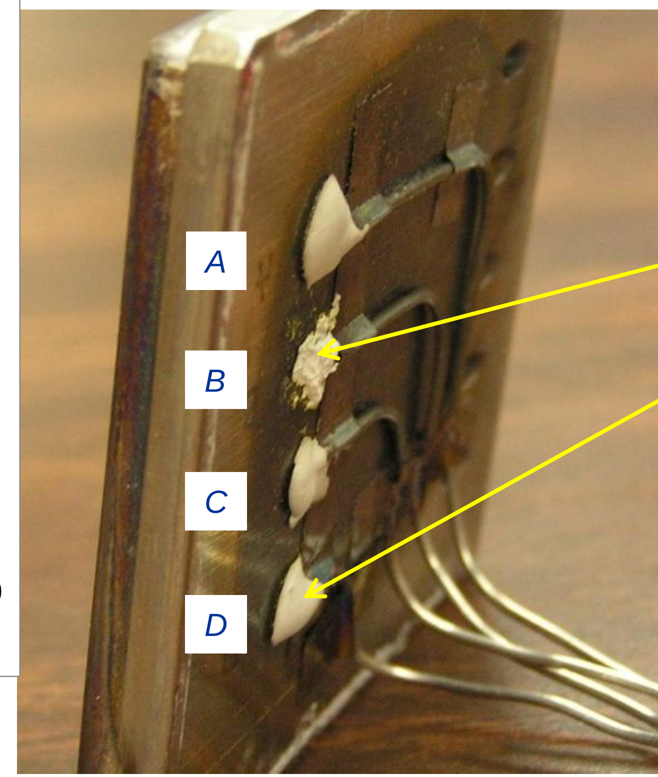
Cold Side Temperature Measurements



Approx. 2 hole diameters from trailing edge of hole





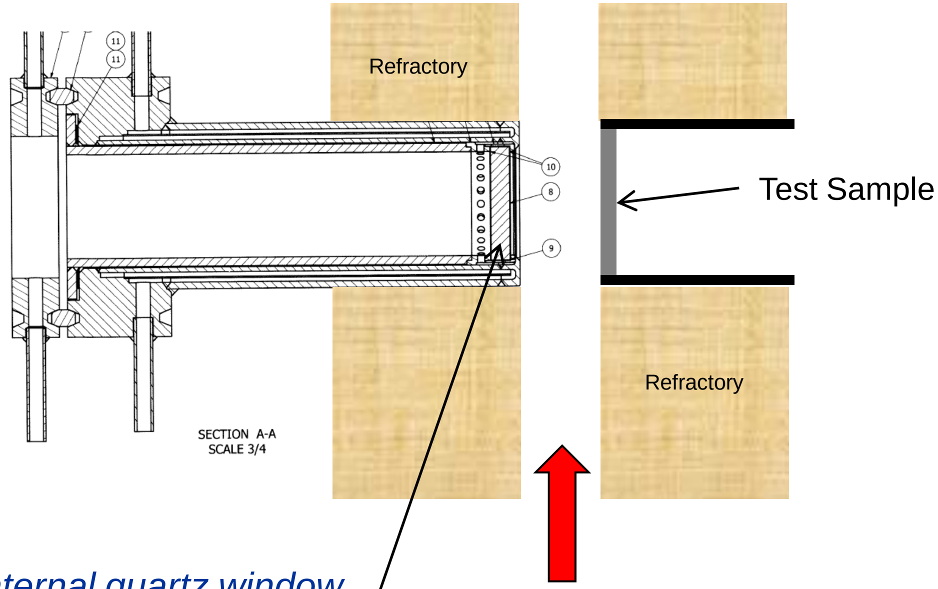


Hot

Cold

Surface Temperature Measurement Approach

- **Emissivity Corrected Pyrometer**
  - Measures surface emissivity @ 905nm
- **B&W CCD camera**
  - Bandpass (900nm) filter
  - Calibrated against BB source

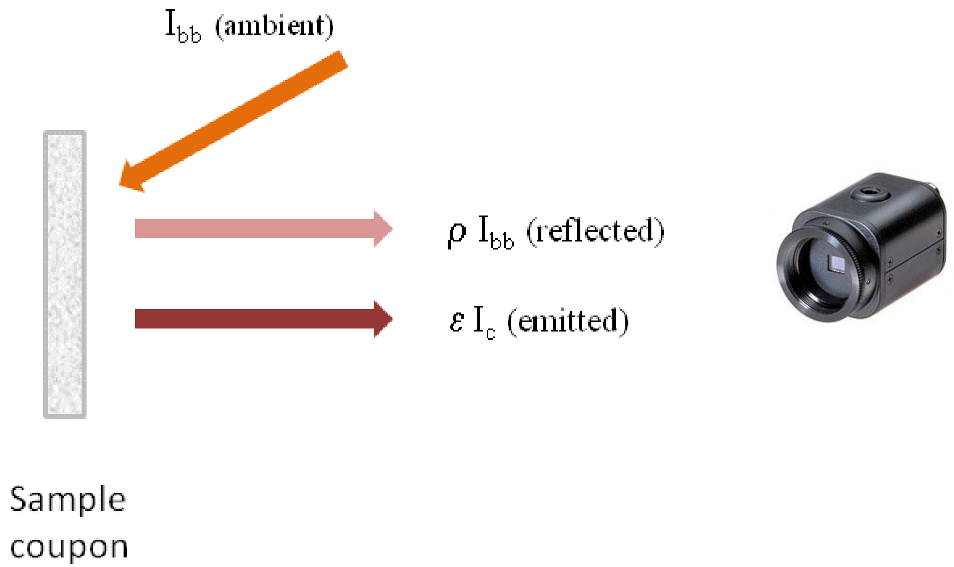


External quartz window for pressure boundary (not shown here)

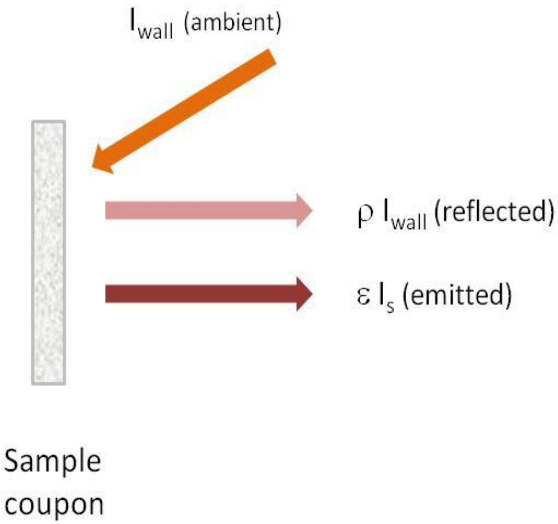
Internal quartz window to provide smooth internal flow path

Hot Surface Temperature Measurement Issues

- **Optical approach cannot differentiate between reflected and emitted photons**
  - Uncertainty analysis to understand impact
  - Design of a multi-color probe in progress (Apogee Scientific)
  - Developing other options too!



Uncertainty Analysis

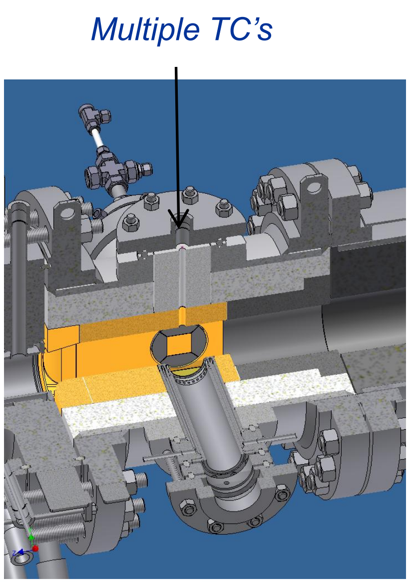


- **Measured signal is sum of reflected and emitted radiation**

$$I_{meas} = (1 - \varepsilon) \cdot I_{wall} + \varepsilon \cdot I_s$$

- **In this simplified approach, assume aerothermal module interior (except test coupon) behaves as blackbody. With Wien's approx. to Planck's law -**

$$I_i = \frac{2 \cdot h \cdot c^2}{\lambda^5} \cdot e^{\left(\frac{-C_2}{\lambda \cdot T_i}\right)}$$

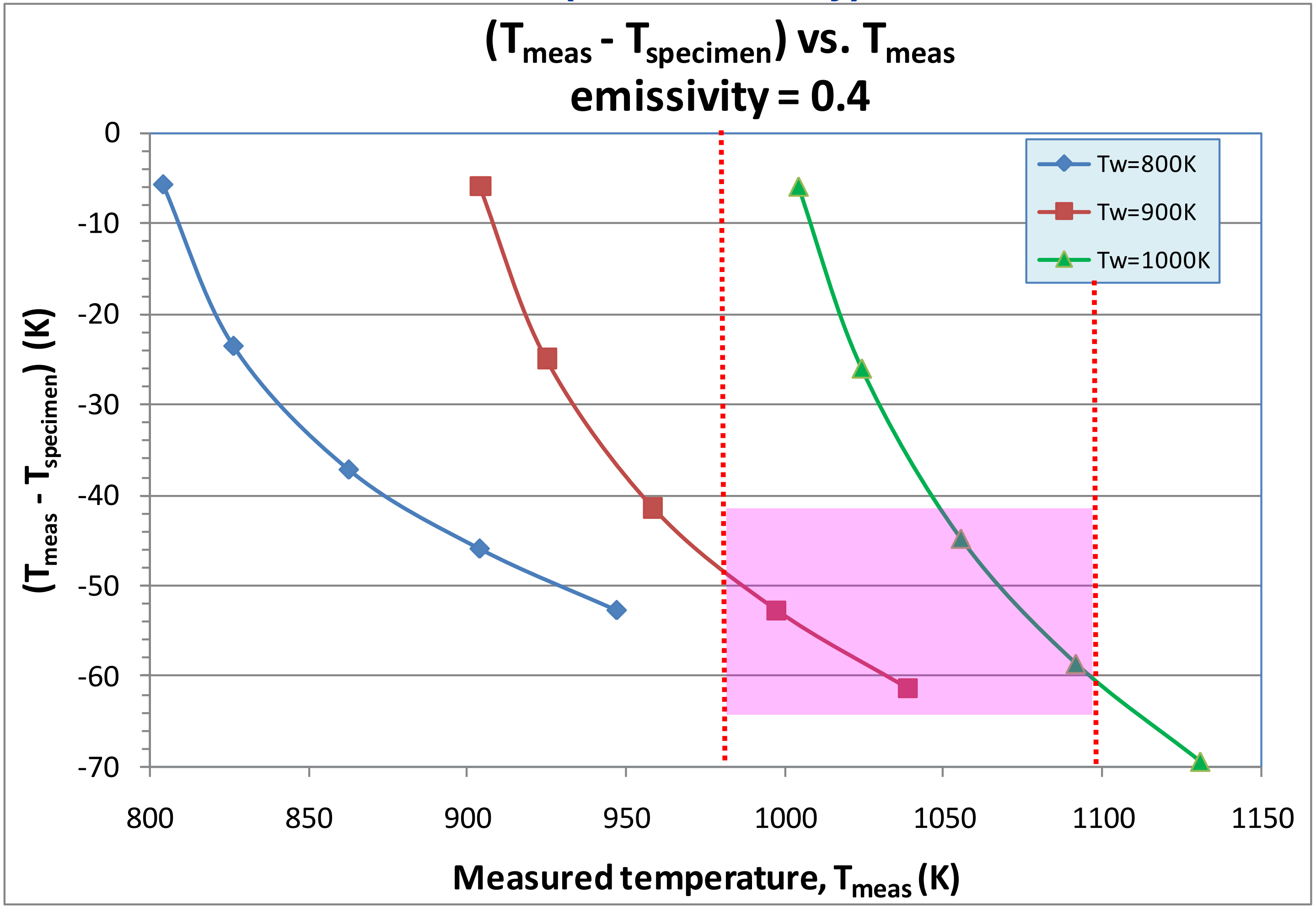


- **The sample-coupon temperature can then be written:**

$$T_s = \frac{-C_2}{\lambda} \cdot \frac{1}{\ln\left[\frac{1}{\varepsilon} \cdot e^{\frac{-C_2}{\lambda} \cdot \frac{1}{T_{meas}}} - \left(\frac{1 - \varepsilon}{\varepsilon}\right) \cdot e^{\frac{-C_2}{\lambda} \cdot \frac{1}{T_{wall}}}\right]}$$

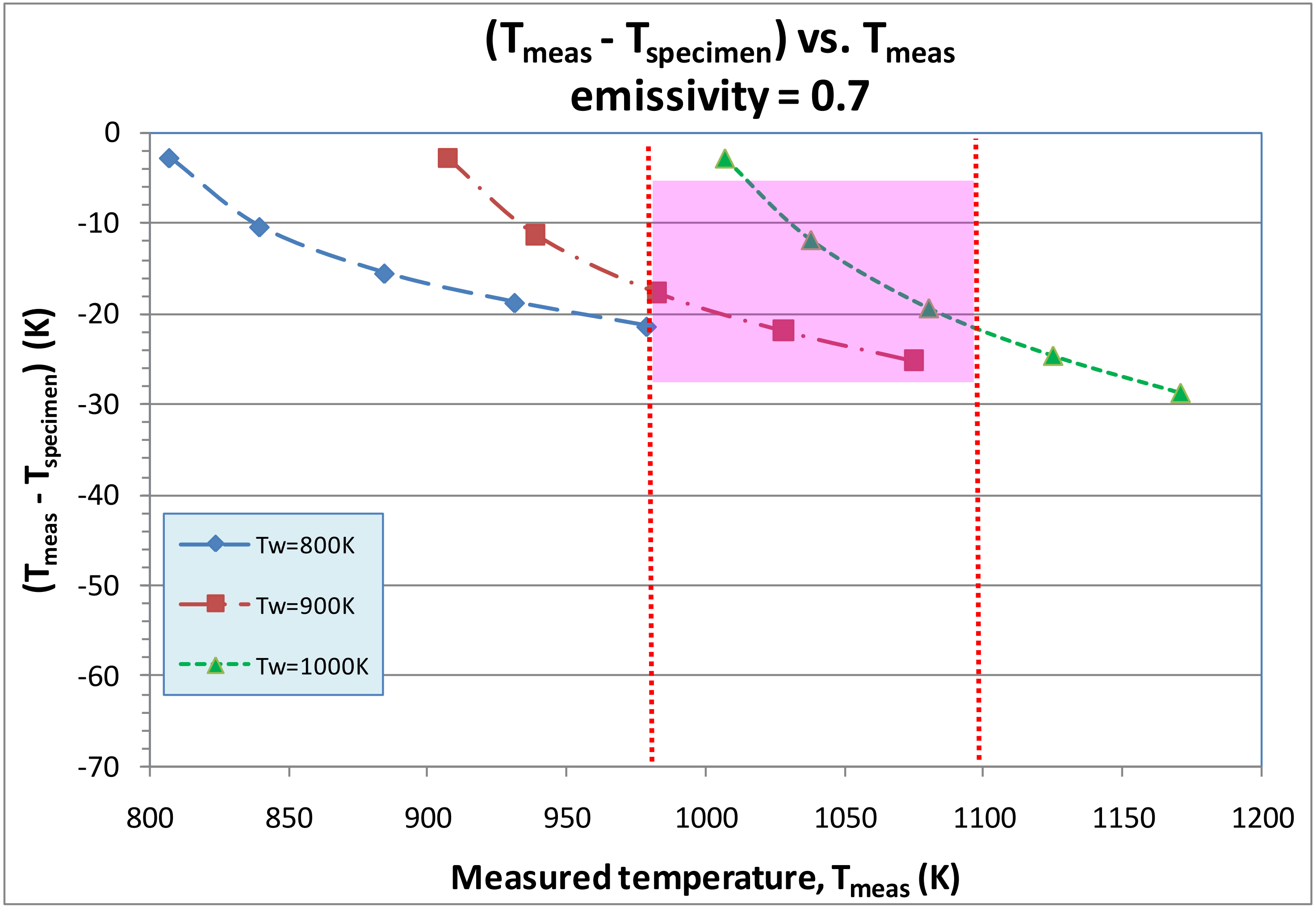
Estimated Bias In IR Mapping

(Low emissivity)



Estimated Bias In IR Mapping

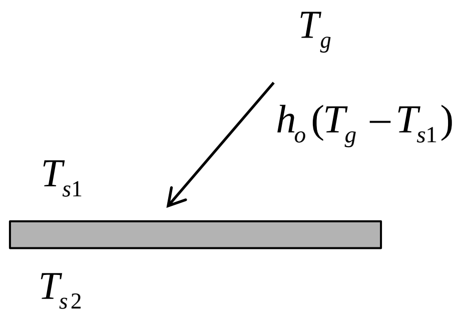
(High emissivity)



Criteria for Uncertainty?

Variability of +/- 25% in the external convective heat transfer coefficient is <u>acceptable</u>

$$\frac{k}{t}(T_{s1}-T_{s2})$$



$$h_o(T_g - T_{s1}) = \frac{k}{t}(T_{s1}-T_{s2})$$

What is the <u>acceptable</u> level of variation in the hot-side surface temperature, T_{s1} ?

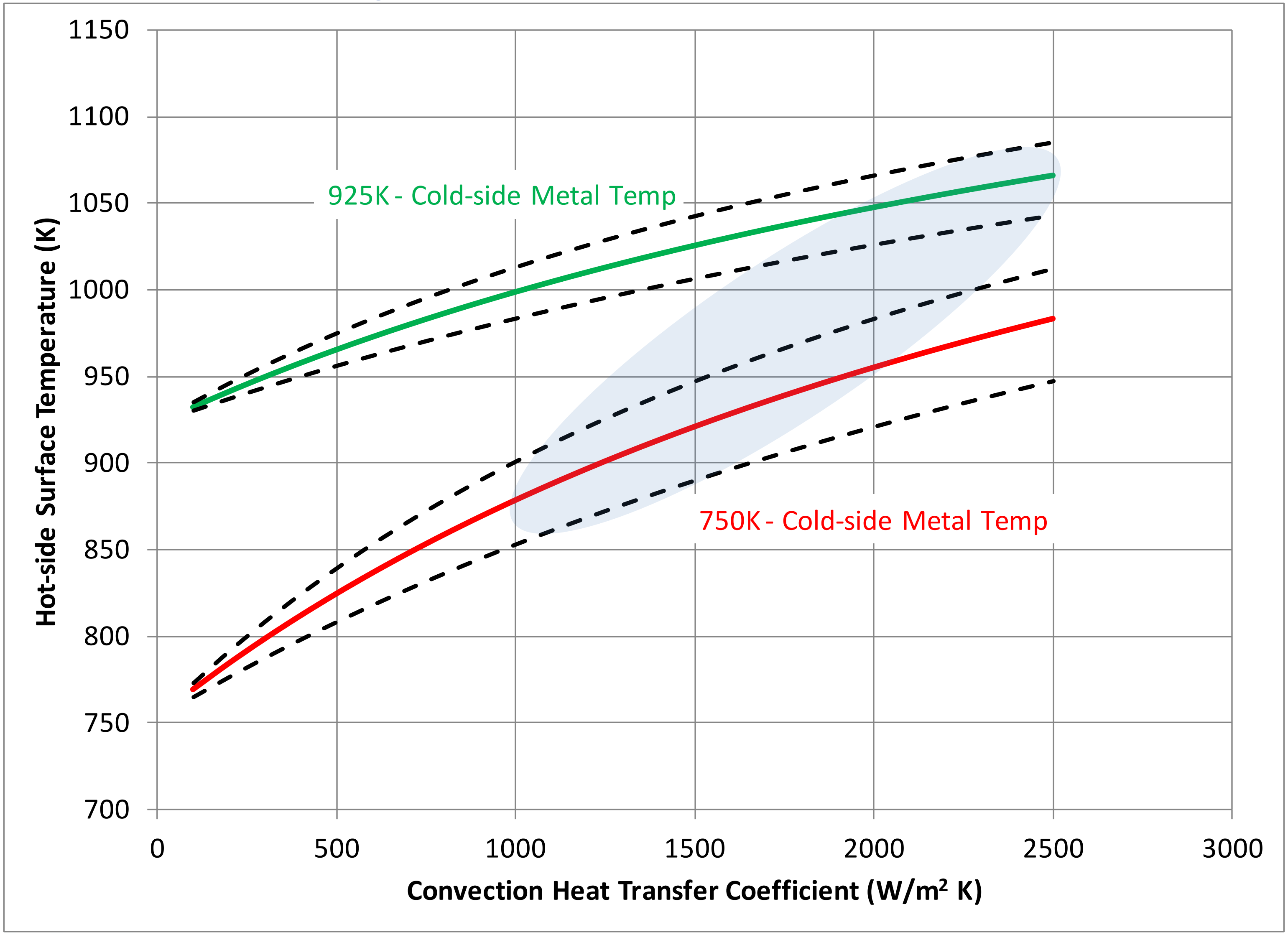
Fixed: *Fixed:* *Bounded by experimental observations*

$$T_{s1} = \frac{\frac{t \cdot h_o}{k} T_g + T_{s2}}{1 + \frac{t \cdot h_o}{k}}$$

K=k(T)

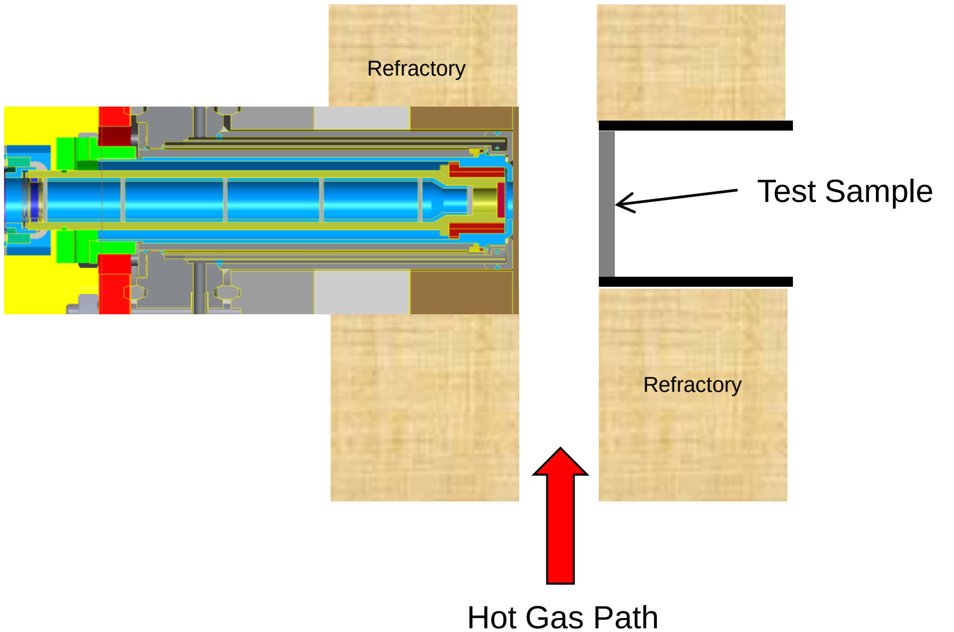
Criteria for Uncertainty?

(T_{gas}=1000C, thickness = 0.25")



TIS -- An Accurate High Speed Alternative

- **Apogee Scientific (small business – Englewood, CO)**
  - High speed thermal imaging system (TIS) applied to combustion processes in reciprocating engines (*Automotive Engineering International, April 2010 and Automotive Design, September 2010*)
- **NETL/Apogee subcontract to design high-temperature thermal imaging system for NETL's Aerothermal Test Rig**
  - Probe design complete

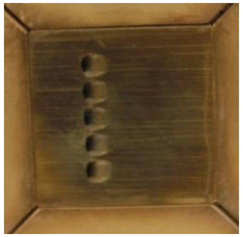


Seeking industrial partnership to continue probe fabrication and testing at simulated turbine conditions

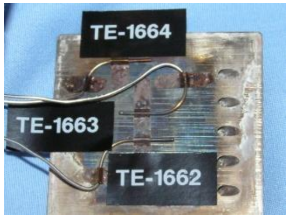
Lessons Learned

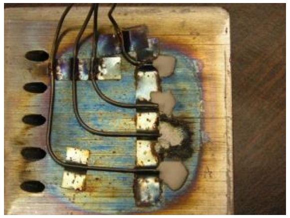
- **Quartz is a robust material, but . . .**
  - Contact stresses can ruin your day
  - Devitrification can ruin your measurement
- **Haynes 230 is a good material, but . . .**
  - Emissivity varies with oxidation
    - Thermal aging effects
    - Measured heat flux varies with exposure time
- **TBCs prevent oxidation but lower emissivity affects optical surface temp. measurements**
- **Attempts to maintain smooth interior walls were not successful**
- **Good surface temperature measurement is an art**

Before Test



After Test

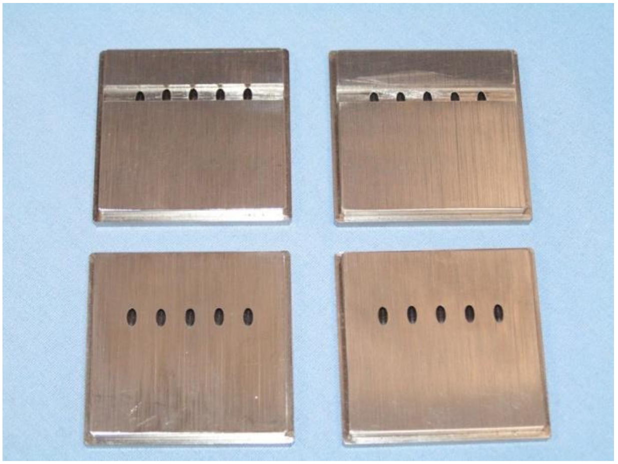




NETL/UNIVERSITY OF PITTSBURGH COLLABORATION ON FILM COOLING SAMPLES

NETL/Pitt Test Plan

- **Fuel composition (natural gas)**
- **Gas temperature**
  - Nominal 1000C (1835F)
  - Minimize devitrification of quartz window
- **Pressure**
  - 1 - 3 atm
- **Mass flowrates in hot gas path**
  - $15{,}000 < Re_L < 60{,}000$
- **Coolant (air) flowrate**
  - Blowing ratio (0-3)



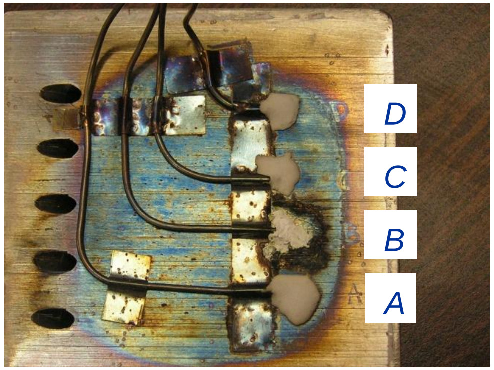
No	Coupon Design	With TBC	Without TBC
1	Flat Plate		√
2	Cylindrical Hole	√	
3			√
4	Cylindrical Hole in Trench	√	
5			√
6	Shaped-Laidback Fan Hole		√

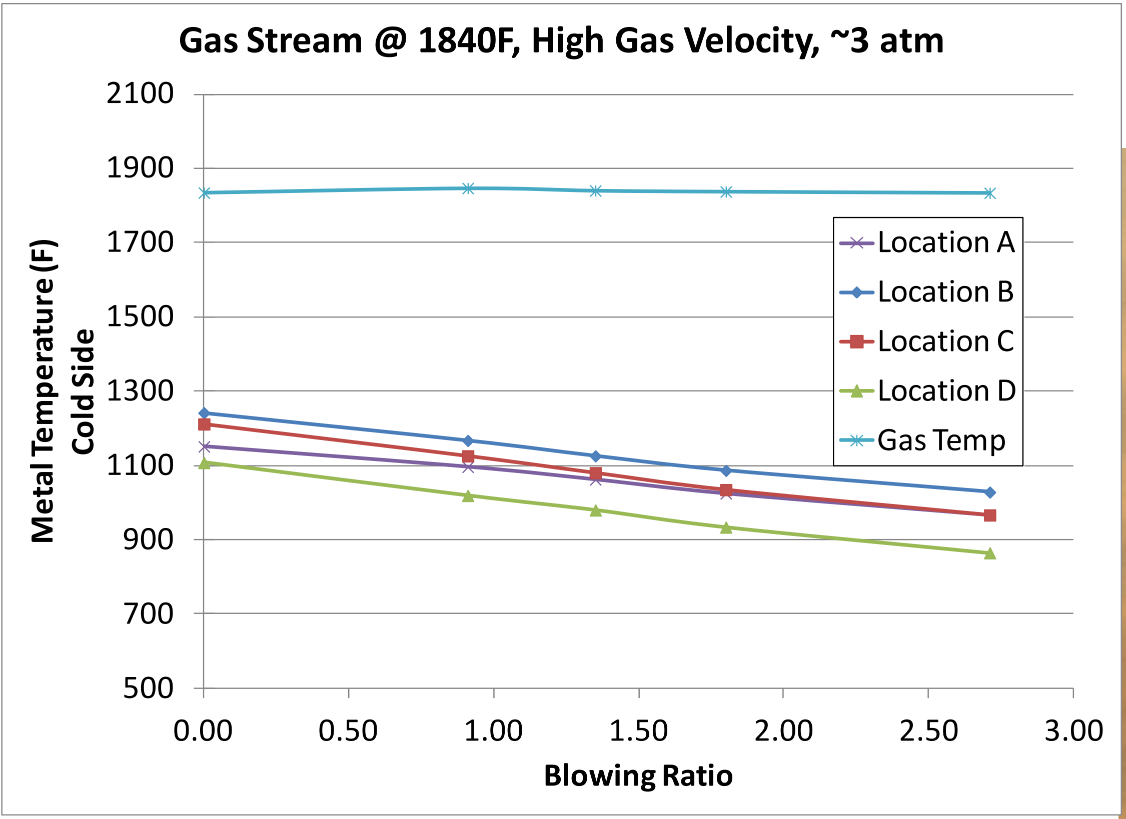
NETL/Pitt Collaboration Status Summary

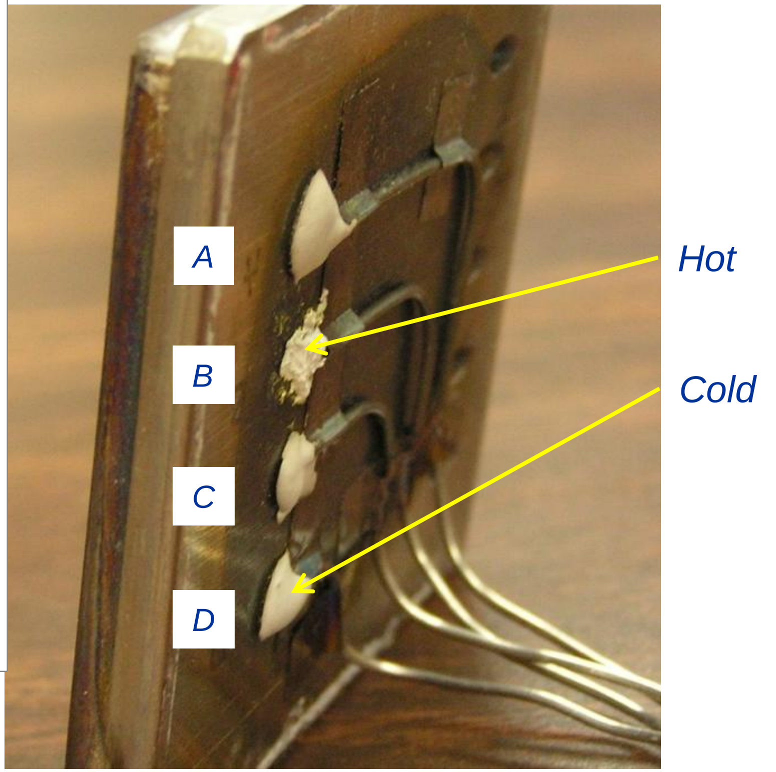
- **Five film cooled coupons tested**
  - 30 degree cylindrical hole design
    - Haynes 230
    - Haynes 230/MCrAlY/8-YSZ TBC
  - Trench with 30 degree holes
    - Haynes 230
    - Haynes 230/MCrAlY/8-YSZ TBC
  - Shaped hole @ 30 degrees
    - Haynes 230

Trench Coupon – Backside TC

Approx. 2 hole diameters from trailing edge of hole





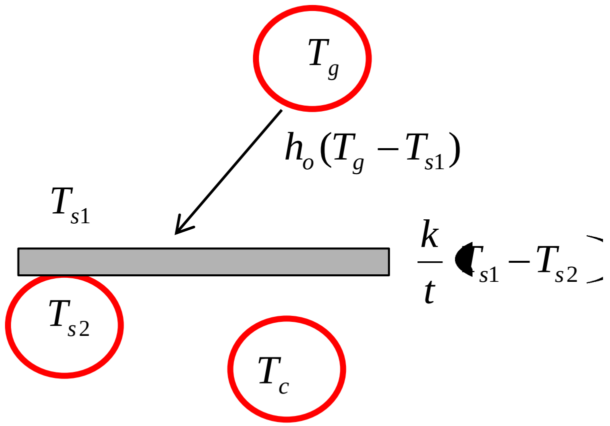


Preliminary Test Results

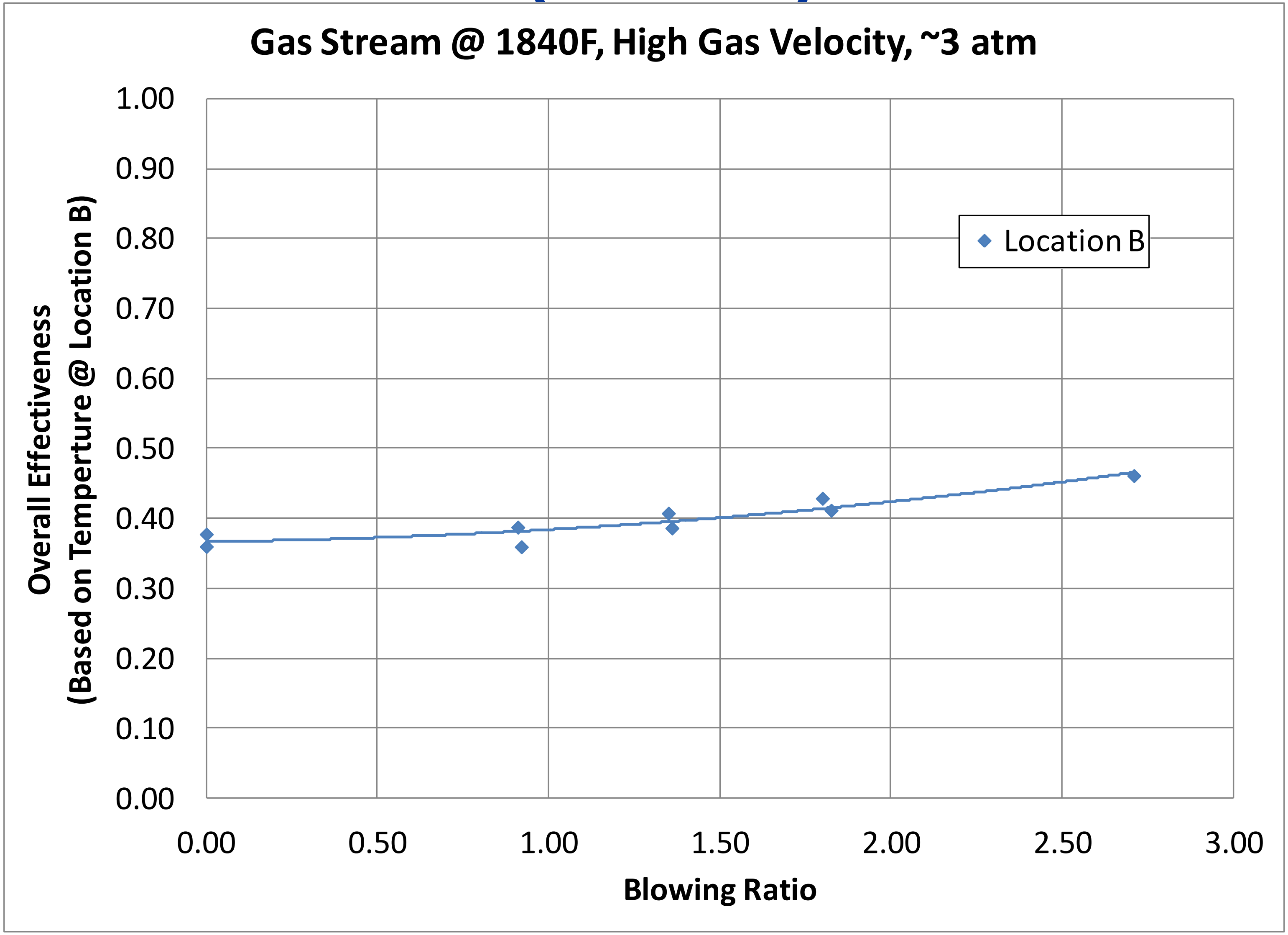
- **Welded TC leads seem to provide highest temperature**

- **Performance indicator**
  - Overall effectiveness

$$\phi = \frac{T_g - T_{s2}}{T_g - T_c}$$



Trench Coupon – Repeatability (No TBC)



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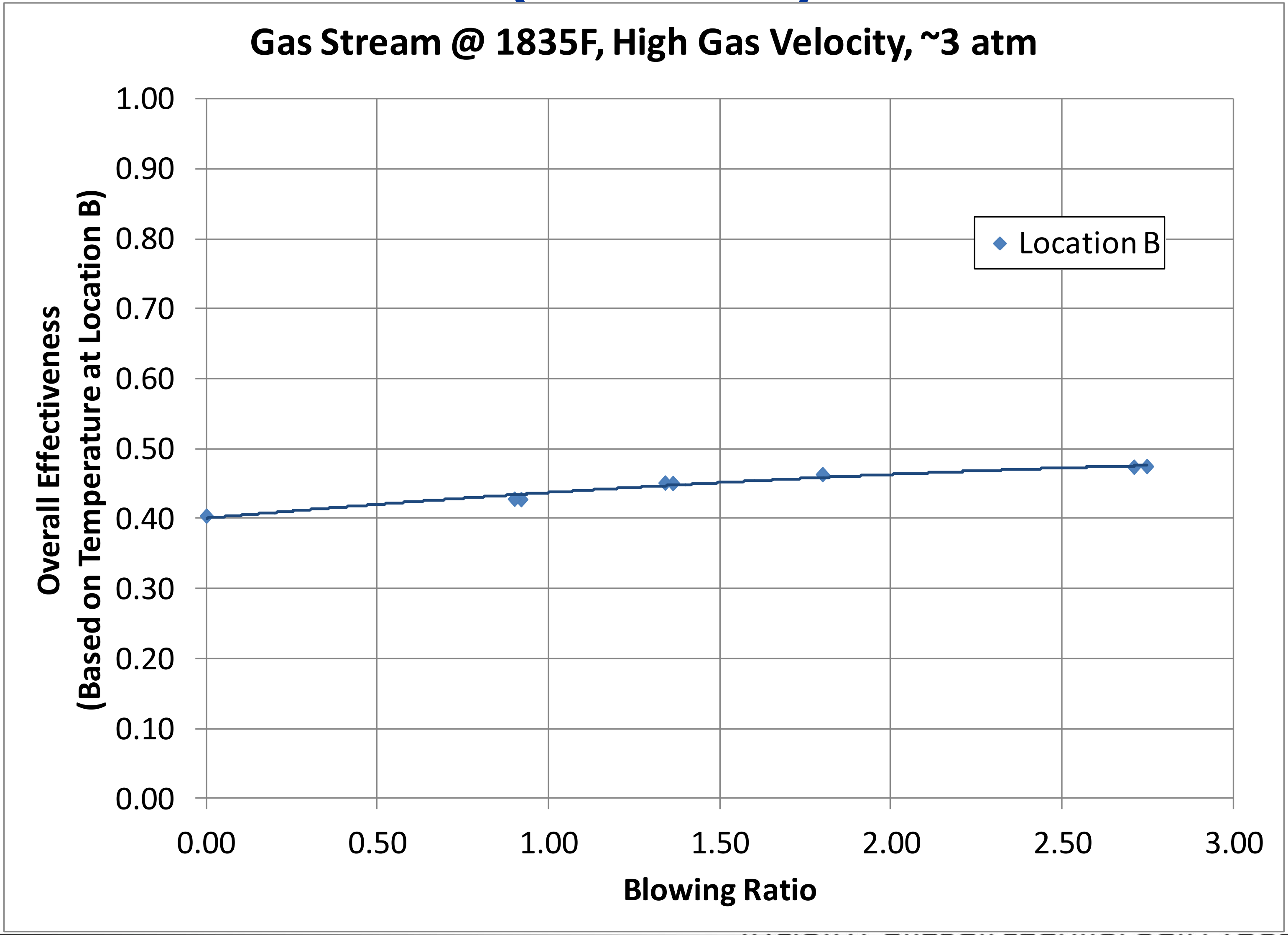
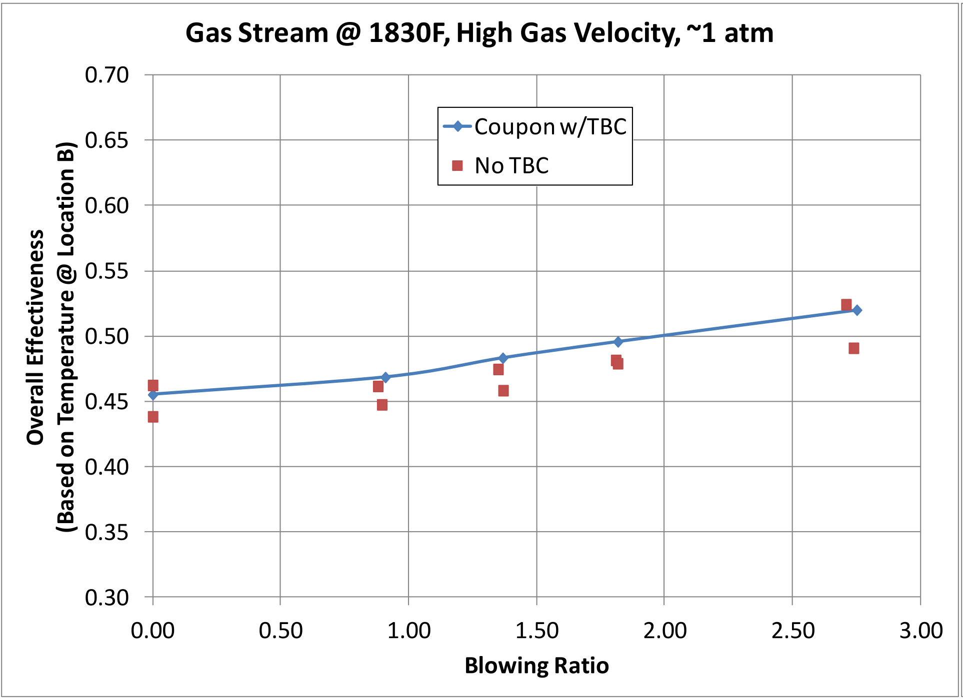
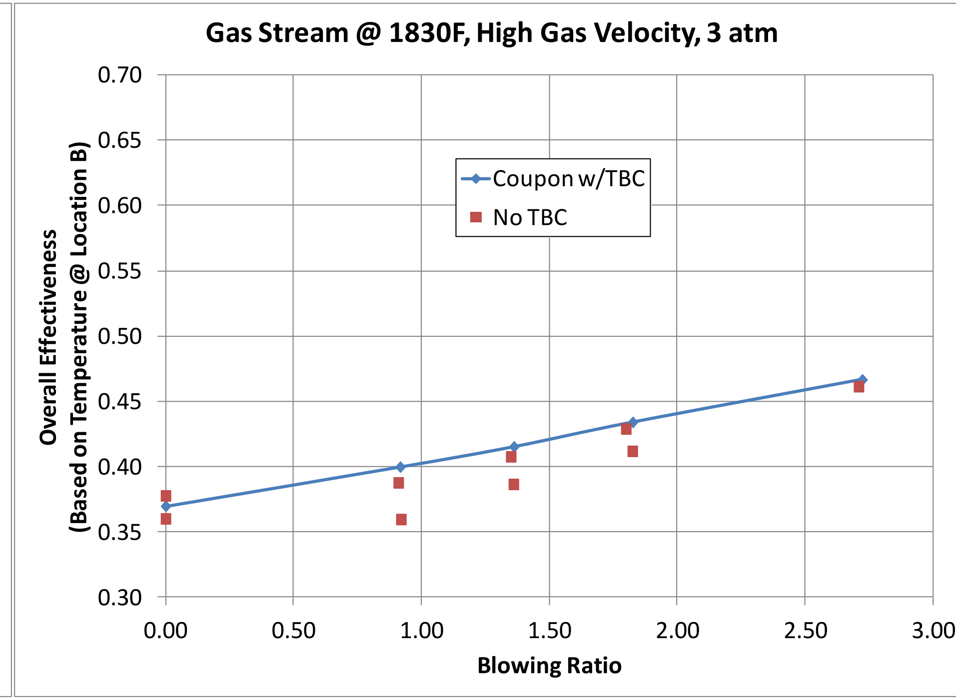
30 deg Cylindrical Hole Coupon – Repeatability (with TBC)

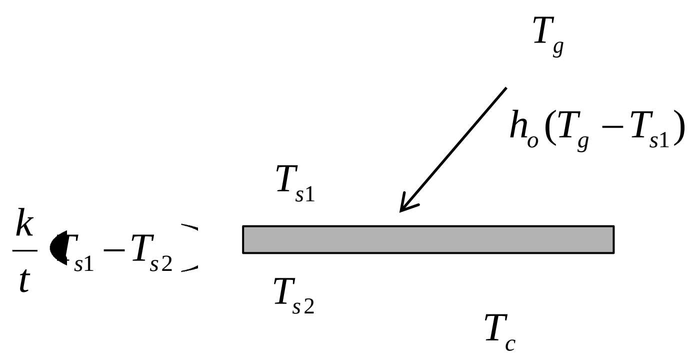


TBC Effects - Trench Coupon

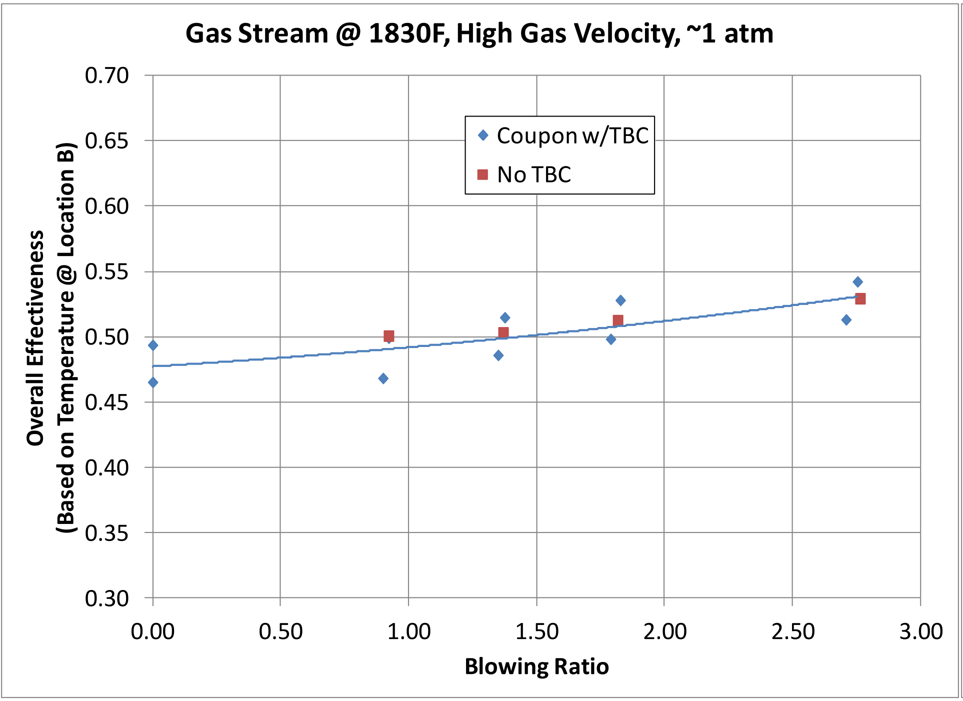


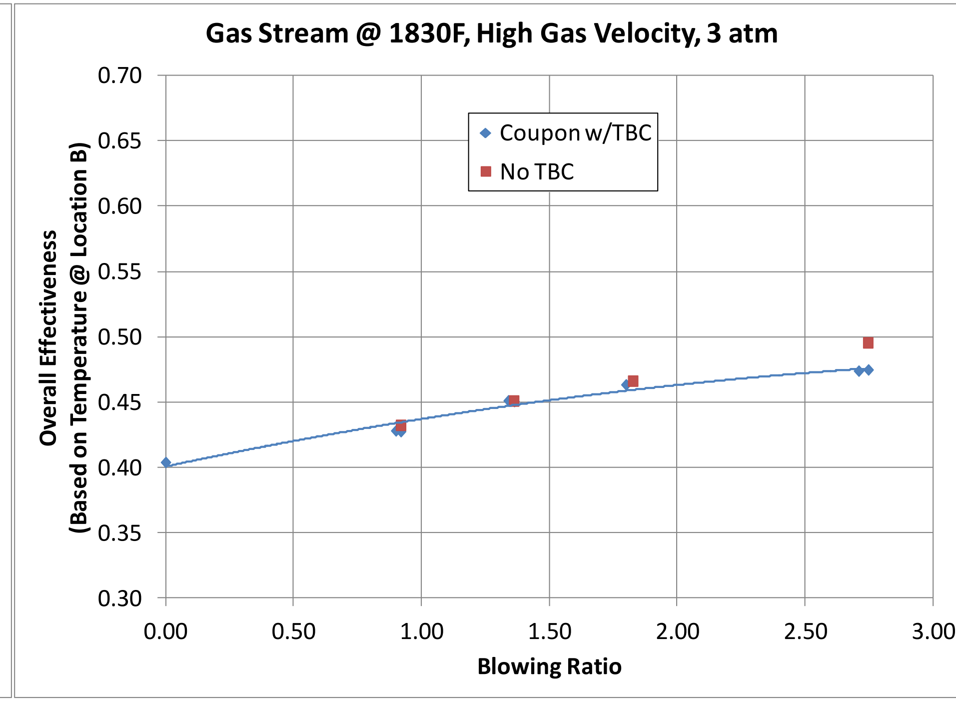


$$\phi = \frac{T_g - T_{s2}}{T_g - T_c}$$

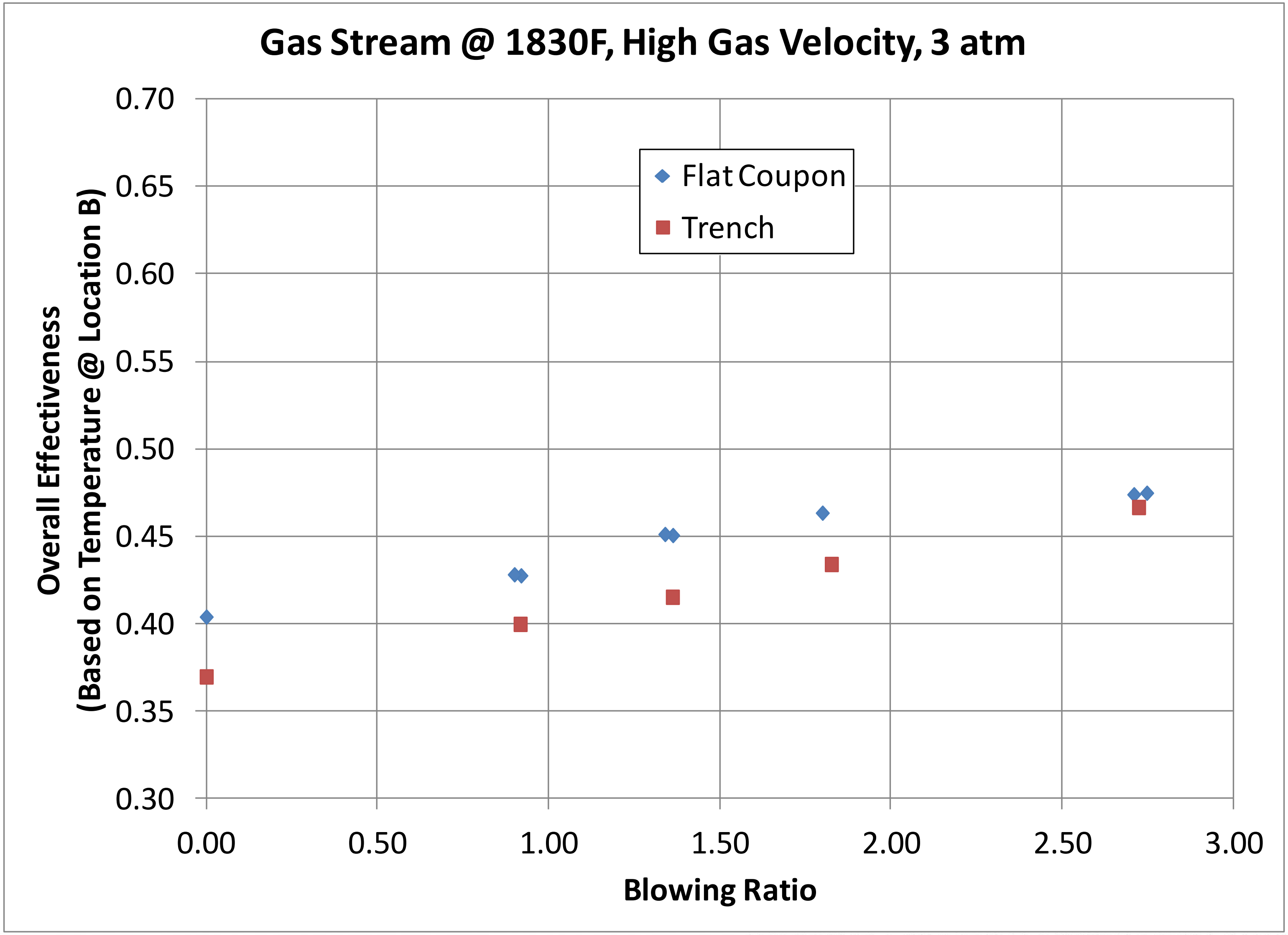


TBC Effects – Cylindrical Hole Coupon



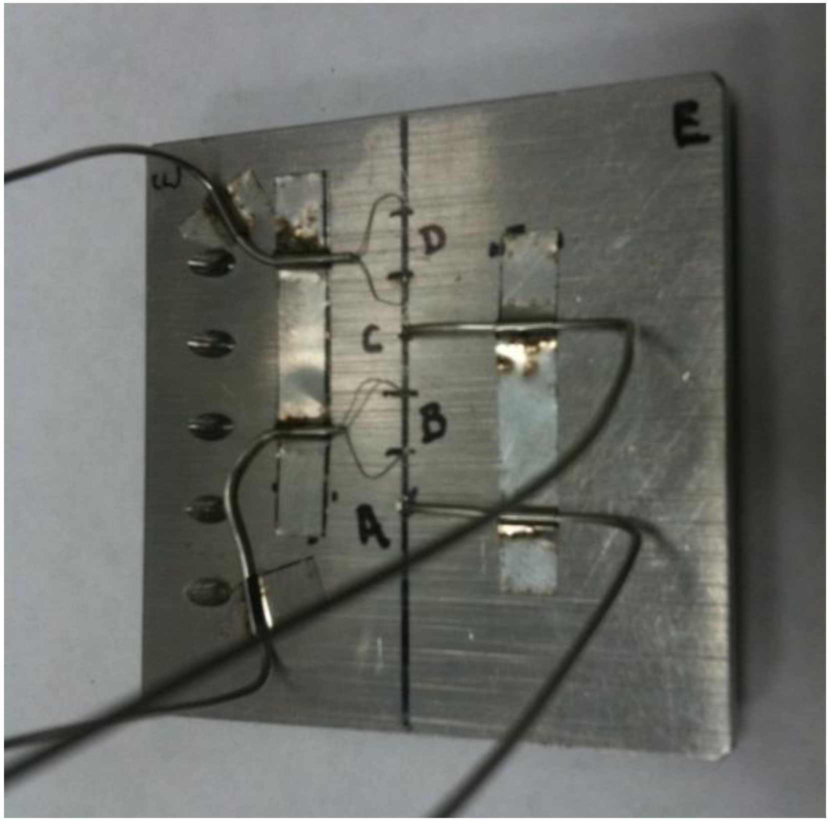


Trench Coupon vs Cylindrical Hole Coupon With TBC

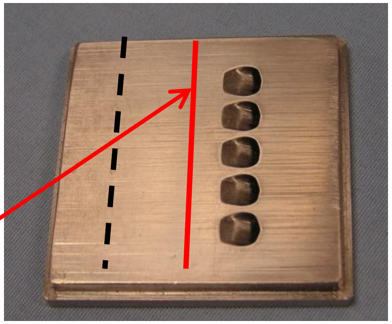


Fan-Shaped Hole Coupon

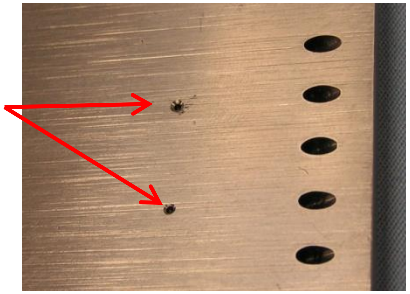
- **TC attachment approach was changed**
  - Two embedded TC's
  - Two TC's welded to surface



New Line of Backside TC Locations

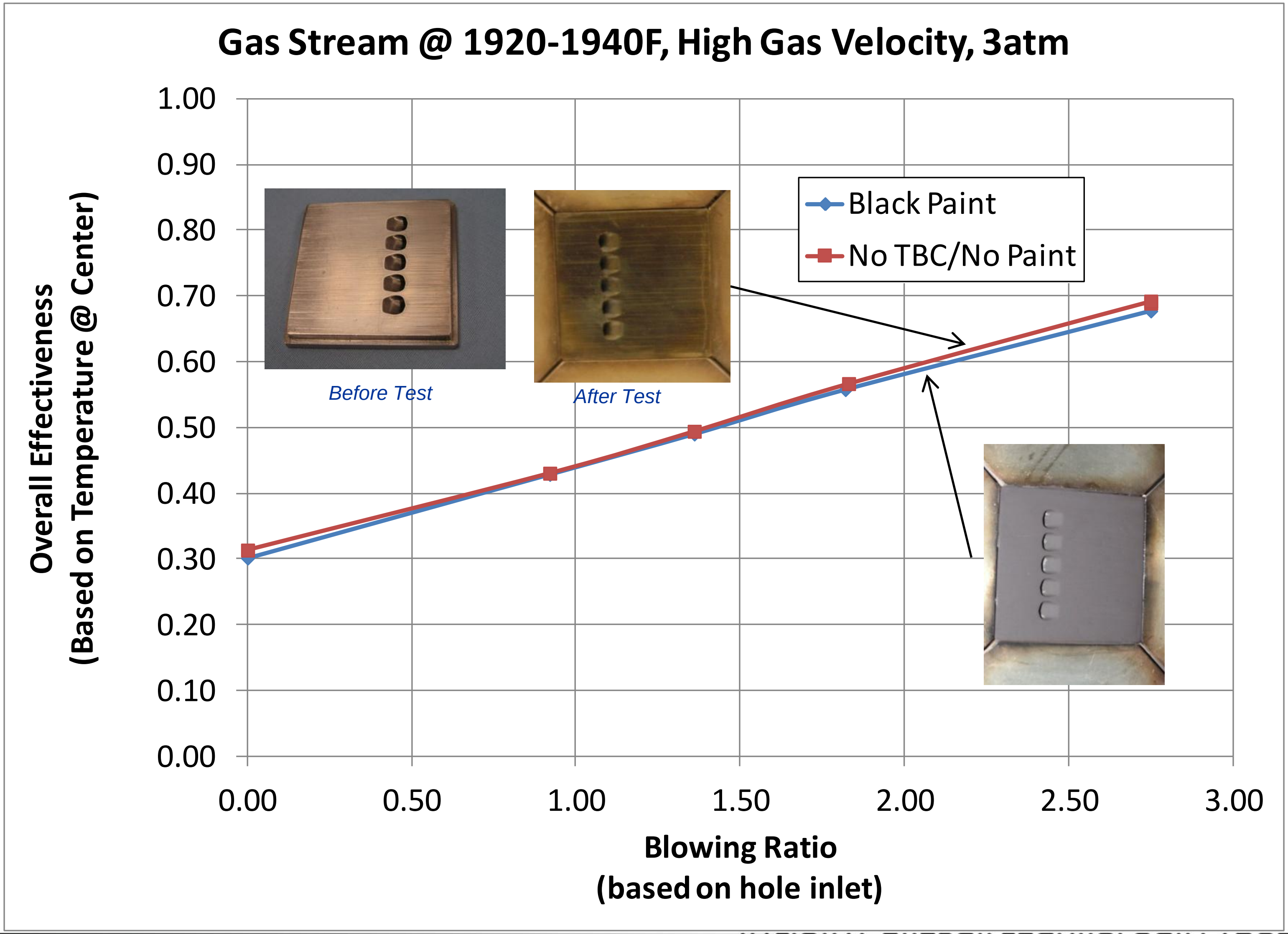


TC's embedded 50% of thickness

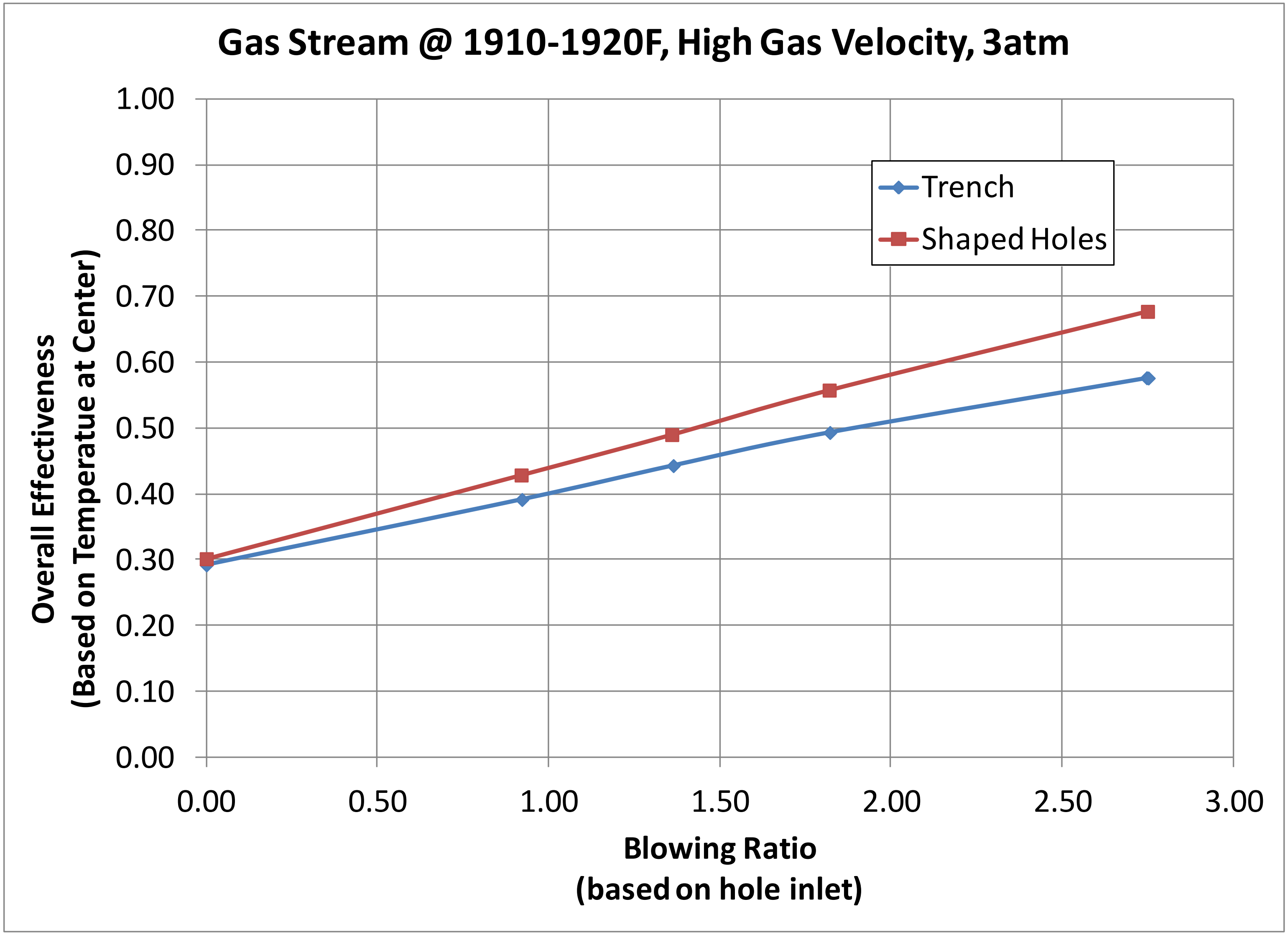


TC's welded equidistance between embedded TC's

Fan-Shaped Hole Coupon (Painted Black vs As-Machined)



Trench Coupon vs Shaped Holes

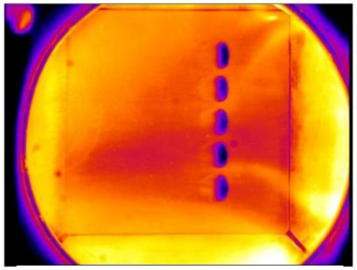


Thermal Images of Hot Side

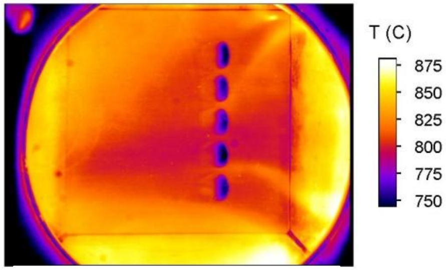
(Coupons Painted Black; Function of Blowing Ratio, BR)

Shaped Hole Coupon

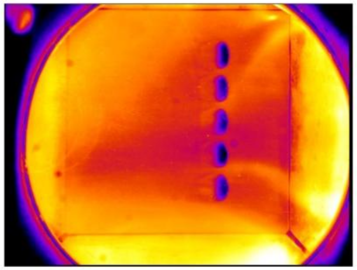
BR = 2.75



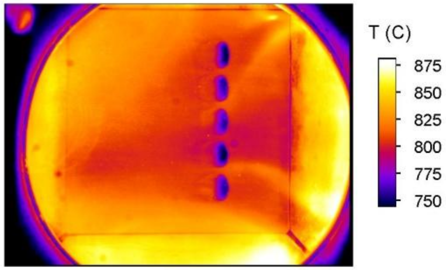
BR = 1.82



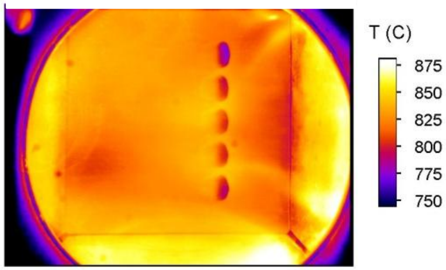
BR = 1.36



BR = 0.92

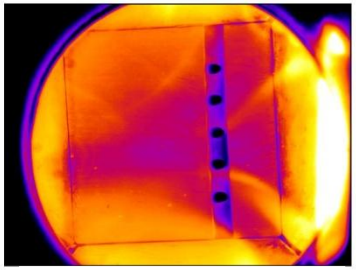


BR = 0

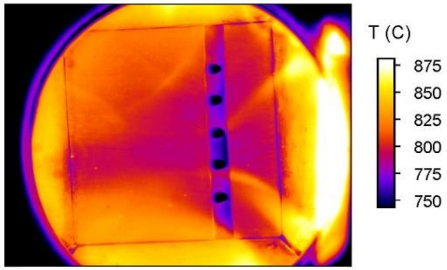


Trench Coupon

BR = 2.75



BR = 1.82



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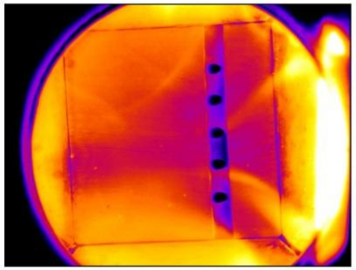

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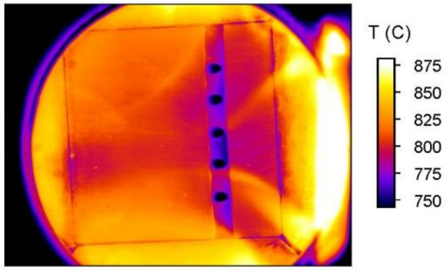

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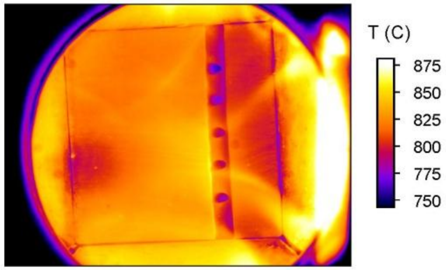
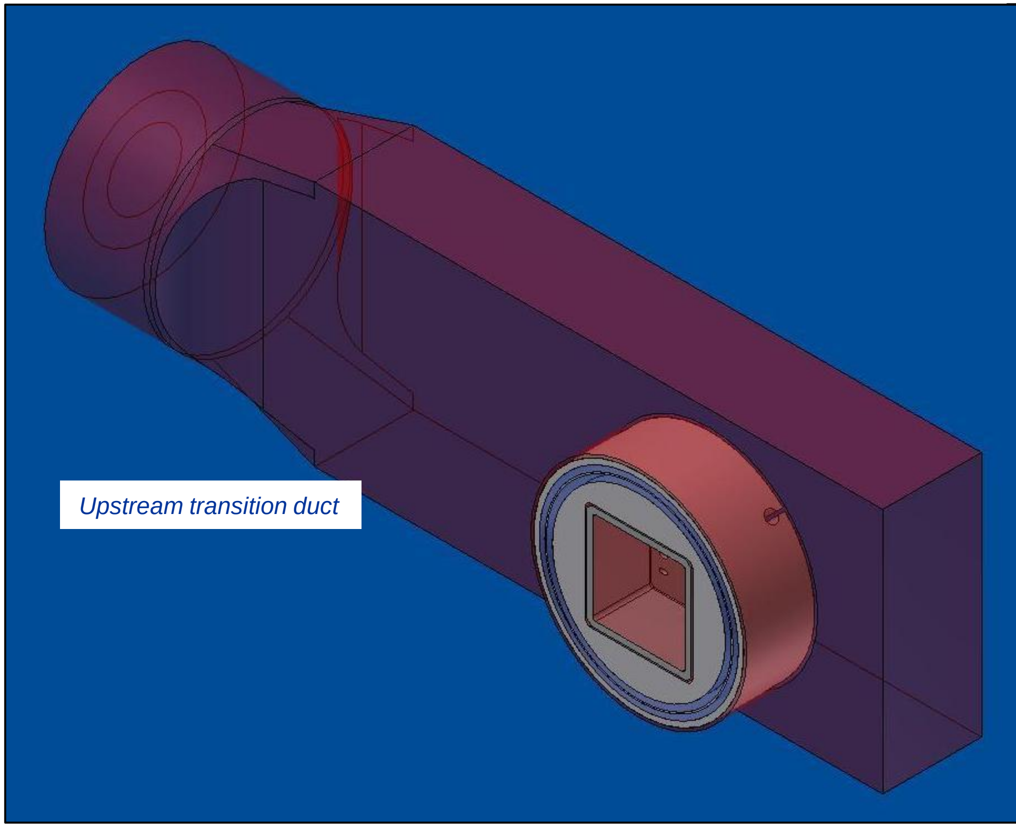
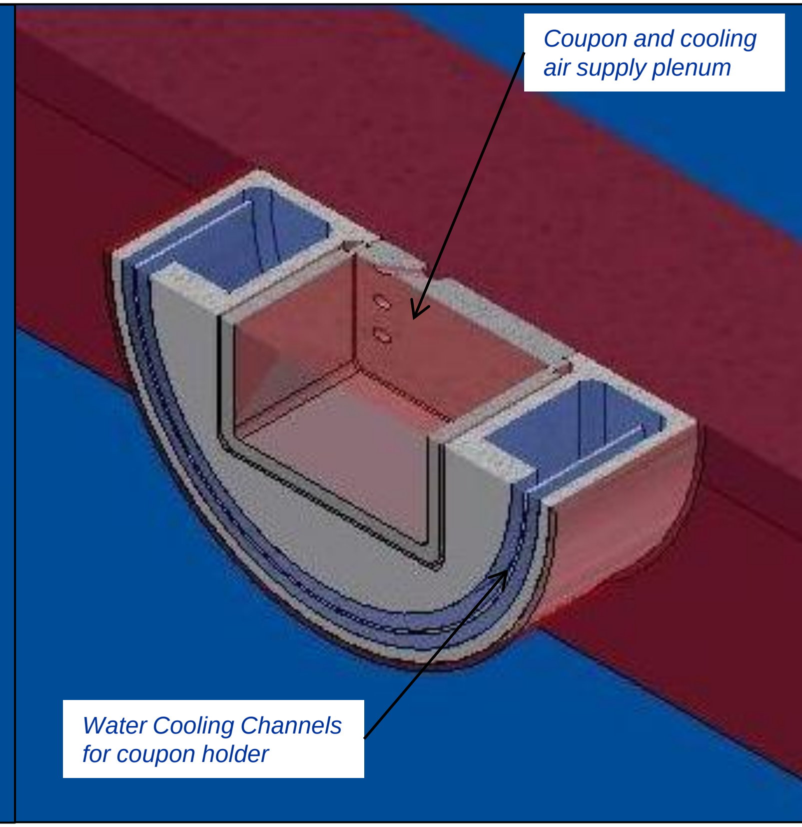


Current Status of Test Rig

- **Preliminary film cooling coupon tests completed**
  - University of Pittsburgh
- **Develop In-situ LDV Capabilities**
  - All safety documentation has been addressed and permit to operate has been received
  - Laser safety enclosure designed, installed, and tested
  - Laser power supply failed during shakedown testing
- **Ash Deposition Studies (WVU)**
  - Particle seeder calibration complete
  - Hot shakedown testing started

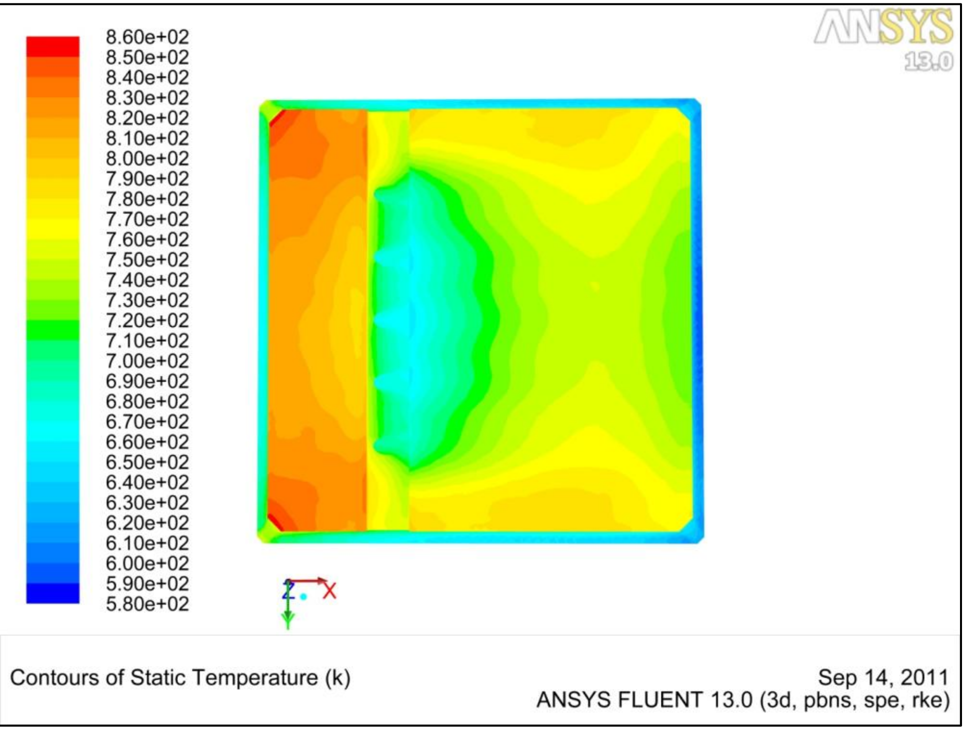
Plans for FY12 to Include CFD Effort Using Commercial Software



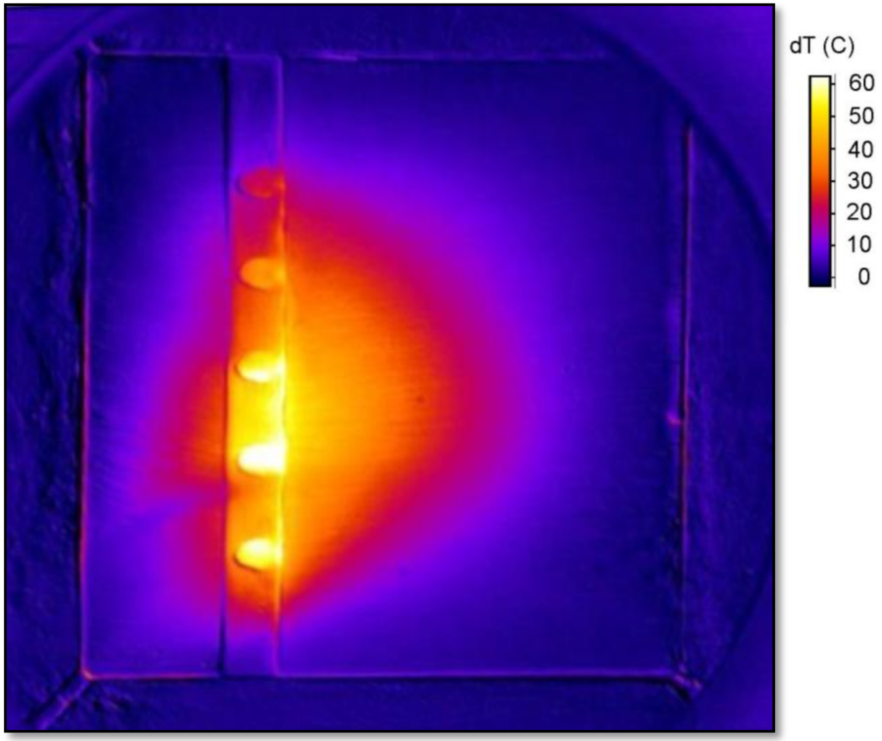


Preliminary CFD Results

Preliminary CFD Results



Experimental Results



Summary

- **NETL high temperature test facility is operational**
  - Some improvement required for non-contact IR temperature mapping
- **Preliminary film cooling tests completed**
  - University of Pittsburgh
- **In-situ LDV capability is in place**
  - Testing postponed due to laser repairs
- **Ash deposition capability is in place**
  - West Virginia University
- **Developing CFD capability using ANSYS/Fluent Software**
- **University and industrial collaboration is encouraged**